AFRL-AFOSR-VA-TR-2016-0065

WORKING BEYOND MOORE LIMIT - COHERENT NONLINEAR OPTICAL CONTROL OF INDIVIDUAL AND COPULED SINGLE ELECTRON DOPED QUANTUM DOTS

Duncan Steel
UNIVERSITY OF MICHIGAN

07/06/2015
Final Report

DISTRIBUTION A: Distribution approved for public release.

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ RTA1
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
	FINAL	6/1/09 - 5/31/15

4. TITLE AND SUBTITLE
Working Beyond Moore's Limit - Coherent Nonlinear Optical Control of Individual and Coupled Single Electron Doped Quantum Dots

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-09-1-0457

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Duncan G. Steel

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Regents of the University of Michigan
3003 S State St
Ann Arbor, MI 48109-1274

8. PERFORMING ORGANIZATION REPORT NUMBER
F022917

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
USAF, AFRL
AF Office of Scientific Research
875 North Randolph Street, RM 3112
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
AFOSR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRIBUTION A

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Work on this program was aimed at developing and understanding nano-optical structures with emphasis on developing quantum optical based devices. Specific work focused on semiconductor quantum dots. During this research period, a number of important discoveries were made as well as critical demonstrations of importance to future technology. The discoveries include (1) Measurement of dynamic nuclear spin polarization kinetics for fluctuation freezing, a result that extends the coherence time of the electron spin by over 2 orders of magnitude; (2) Design and demonstration of coherent optical control steps in preparation for deterministic spin-photon entanglement; (3) Demonstration of initialization of the 2 qubit states; (4) Demonstration of nonlocal nuclear spin freezing in quantum dot molecules; (5) Measurement of the Overhauser magnetic field distribution before and after fluctuation freezing; and (6) Demonstration of a flying qubit by entanglement of the quantum dot spin polarization with the polarization of a spontaneously emitted photon. Future work is focusing on use of cavity enhanced quantum dots for demonstration teleportation between information contained in a spontaneous photon down conversion source to a quantum dot spin.

15. SUBJECT TERMS
Quantum information, semiconductor quantum dots, coherent optical control, all optical control gates, optical control of the nuclear field, nuclear spin fluctuation quieting (freezing).

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Kullie Kennedy
U	U	U	UU		**19b. TELEPHONE NUMBER** *(Include area code)* 734-763-6438

Reset

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18
Adobe Professional 7.0

INSTRUCTIONS FOR COMPLETING SF 298

1. REPORT DATE. Full publication date, including day, month, if available. Must cite at least the year and be Year 2000 compliant, e.g. 30-06-1998; xx-06-1998; xx-xx-1998.

2. REPORT TYPE. State the type of report, such as final, technical, interim, memorandum, master's thesis, progress, quarterly, research, special, group study, etc.

3. DATES COVERED. Indicate the time during which the work was performed and the report was written, e.g., Jun 1997 - Jun 1998; 1-10 Jun 1996; May - Nov 1998; Nov 1998.

4. TITLE. Enter title and subtitle with volume number and part number, if applicable. On classified documents, enter the title classification in parentheses.

5a. CONTRACT NUMBER. Enter all contract numbers as they appear in the report, e.g. F33615-86-C-5169.

5b. GRANT NUMBER. Enter all grant numbers as they appear in the report, e.g. AFOSR-82-1234.

5c. PROGRAM ELEMENT NUMBER. Enter all program element numbers as they appear in the report, e.g. 61101A.

5d. PROJECT NUMBER. Enter all project numbers as they appear in the report, e.g. 1F665702D1257; ILIR.

5e. TASK NUMBER. Enter all task numbers as they appear in the report, e.g. 05; RF0330201; T4112.

5f. WORK UNIT NUMBER. Enter all work unit numbers as they appear in the report, e.g. 001; AFAPL30480105.

6. AUTHOR(S). Enter name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. The form of entry is the last name, first name, middle initial, and additional qualifiers separated by commas, e.g. Smith, Richard, J, Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES). Self-explanatory.

8. PERFORMING ORGANIZATION REPORT NUMBER. Enter all unique alphanumeric report numbers assigned by the performing organization, e.g. BRL-1234; AFWL-TR-85-4017-Vol-21-PT-2.

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES). Enter the name and address of the organization(s) financially responsible for and monitoring the work.

10. SPONSOR/MONITOR'S ACRONYM(S). Enter, if available, e.g. BRL, ARDEC, NADC.

11. SPONSOR/MONITOR'S REPORT NUMBER(S). Enter report number as assigned by the sponsoring/ monitoring agency, if available, e.g. BRL-TR-829; -215.

12. DISTRIBUTION/AVAILABILITY STATEMENT. Use agency-mandated availability statements to indicate the public availability or distribution limitations of the report. If additional limitations/ restrictions or special markings are indicated, follow agency authorization procedures, e.g. RD/FRD, PROPIN, ITAR, etc. Include copyright information.

13. SUPPLEMENTARY NOTES. Enter information not included elsewhere such as: prepared in cooperation with; translation of; report supersedes; old edition number, etc.

14. ABSTRACT. A brief (approximately 200 words) factual summary of the most significant information.

15. SUBJECT TERMS. Key words or phrases identifying major concepts in the report.

16. SECURITY CLASSIFICATION. Enter security classification in accordance with security classification regulations, e.g. U, C, S, etc. If this form contains classified information, stamp classification level on the top and bottom of this page.

17. LIMITATION OF ABSTRACT. This block must be completed to assign a distribution limitation to the abstract. Enter UU (Unclassified Unlimited) or SAR (Same as Report). An entry in this block is necessary if the abstract is to be limited.

FINAL REPORT
To
THE AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

Working Beyond Moore's Limit - Coherent Nonlinear Optical Control of Individual and Coupled Single Electron Doped Quantum Dots

AFOSR GRANT NO. FA9550-09-1-0457

***GRANT PERIOD:** 6/1/09 - 5/31/15*

Principal Investigator: Duncan G. Steel, The Robert J. Hiller Professor
Department of Electrical Engineering and Computer Science, Department of Physics
Harrison M. Randall Laboratory of Physics
The University of Michigan
Ann Arbor, MI 48109
Phone: 734-764-4469
Email: dst@umich.edu

Abstract

Work on this program was aimed at developing and understanding nano-optical structures with emphasis on developing quantum optical based devices. Specific work focused on epitaxially grown semiconductor quantum dots (QDs). The quantum dots were fabricated in structures that could be biased to control the charge state via the Coulomb blockade and in cavities to enhance the brightness. During this research period, a number of important discoveries were made as well as critical demonstrations of importance to future technology. The discoveries include (1) Measurement of dynamic nuclear spin polarization (DNSP) kinetics leading to fluctuation freezing, a result that extends the coherence time of the electron spin by over 2 orders of magnitude (freezing time ~10msec, lifetime>>1 sec); (2) Design and demonstration of coherent optical control steps in preparation for deterministic spin-photon entanglement; (3) Demonstration of initialization of the 2 qubit states in a vertically coupled quantum dot (a quantum dot molecule); (4) Demonstration of nonlocal nuclear spin fluctuation freezing in vertically coupled quantum dots; (5) Measurement of the Overhauser magnetic field distribution before and after fluctuation freezing showing we are able to optically narrow the nuclear field distribution; (6) Demonstration of active nuclear spin locking in a quantum dot molecule; and (7) Demonstration of a flying qubit by entanglement of the quantum dot spin polarization states with the polarization states of a spontaneously emitted photon; (8) Initiation of a collaboration with Paul Kwiat (Univ Illinois) to build a high brightness spontaneous photon down conversion source for teleportation. Future work is focusing on use of cavity enhanced quantum dots for demonstration teleportation between information contained in a spontaneous photon down conversion source to a quantum dot spin.

PUBLICATIONS

Journal publications

1. Xiaodong Xu, Bo Sun, P. R. Berman, Dan Gammon, L. J. Sham, Duncan G. Steel, "Strong Optical Field Study of a Single Self-Assembled Quantum Dot," invited Solid State Com-

munications **149**, pp1479-1484 (2009).

http://www.sciencedirect.com/science/article/pii/S0038109809002476

2. Erik D. Kim, Katherine Smirl, Xiaodong Xu, Bo Sun, D.G. Steel, A. S. Bracker, D. Gammon, and L. J. Sham, "Fast spin rotations and optically controlled geometric phases in a quantum dot," Phys. Rev. Lett. 104, 167401 (2010). DOI: 10.1103/PhysRevLett.104.167401.

   http://link.aps.org/doi/10.1103/PhysRevLett.104.167401

3. Erik D. Kim, Katherine Truex, Yanwen Wu, A. Amo, Xiaodong Xu, and D. G. Steel*,* A. S. Bracker and D. Gammon*, and* L. J. Sham, "Picosecond Optical Spectroscopy of a Single Negatively Charged Self-Assembled InAs Quantum Dot,", Applied Physics Letters 97, p. 113110 (2010). DOI: 10.1063/1.3487783

   http://scitation.aip.org/content/aip/journal/apl/97/11/10.1063/1.3487783

4. E.D. Kim, K. Truex, X.D. Xu, Bo Sun, D.G. Steel, Allan Bracker, Dan Gammon, L.J. Sham, "Fast optically driven spin qubit gates in an InAs quantum dot. Conference on Advances in Photonics of Quantum Computing, Memory, and Communication III, JAN 27-28, 2010 San Francisco, CA, Book Series: Proceedings of SPIE-The International Society for Optical Engineering **7611** (2010). DOI: 10.1117/12.842072

5. Jing Wang, Ren-Bao Liu, Bang-Fen Zhu, L. J. Sham, and D. G. Steel, "Coherent spin control by electromagnetic vacuum fluctuations" Phys. Rev. A **83,** 053833 (2011). DOI: 10.1103/PhysRevA.83.053833

   http://journals.aps.org/pra/abstract/10.1103/PhysRevA.83.053833

6. Qiong Huang and Duncan S. Steel, "Optical excitation effects on spin-noise spectroscopy in semiconductors," Phys. Rev. B 83, 155204 (2011). DOI:10.1103/PhysRevB.83.155204.

   http://journals.aps.org/prb/abstract/10.1103/PhysRevB.83.155204

7. Bo Sun, Wang Yao, Xiaodong Xu, Allan S. Bracker, Daniel Gammon, L. J. Sham, Duncan Steel , "Persistent Optical Nuclear Spin Narrowing in a Singly Charged InAs Quantum Dot," invited, JOSAB **29** 2, pp A119-A126 (2012).

   http://www.opticsinfobase.org/aop/abstract.cfm?URI=josab-29-2-A119

8. Bo Sun, Colin Ming Earn Chow, and Duncan G. Steel, Allan S. Bracker and Daniel Gammon, L.J. Sham, "Persistent narrowing of nuclear-spin fluctuations in InAs quantum dots using laser excitation," Physical Review Letters, **108** 18, p187401 (2012) DOI: 10.1103/PhysRevLett.108.187401.

http://link.aps.org/doi/10.1103/PhysRevLett.108.187401

9. Katherine Truex, Leon Webster, L.-M. Duan, L. J. Sham, and D. G. Steel "Coherent Control with Optical Pulses for Deterministic Spin-Photon Entanglement" Phys. Rev. B.88, p195306 (2013).

   http://journals.aps.org/prb/abstract/10.1103/PhysRevB.88.195306

10. J. R. Schaibley, A. P. Burgers, G. A. McCracken, and D. G. Steel_ A. S. Bracker and D. Gammon L. J. Sham, "Direct Detection of Time Resolved Rabi Oscillations in a Single Quantum Dot via Resonance Fluorescence", Physical Review B **87** p115311 (2013). **DOI:** 10.1103/PhysRevB.87.11531

    http://journals.aps.org/prb/abstract/10.1103/PhysRevB.87.115311

11. J. R. Schaibley, A. P. Burgers, G. A. McCracken, L-M Duan, P. R. Berman, and D. G. Steel, A. S. Bracker and D. Gammon L. J. Sham, "Demonstration of quantum entanglement between a single quantum dot electron spin and a photon", Physical Review Letters **110**, 167401 (2013). **DOI:** 10.1103/PhysRevLett.110.167401

    http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.110.167401

12. L. A. Webster, K. Truex, L.-M. Duan, D. G. Steel, A. S. Bracker, D. Gammon, and L.J. Sham, "Coherent control to prepare an InAs quantum dot for spin-photon Entanglement," Phys. Rev. Lett. **112**, 126801 (2014). DOI: 10.1103/PhysRevLett.112.126801

    http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.112.126801

14. Steel, DG, "Laser Spectroscopy and Quantum Optics in GaAs and InAs Semiconductor Quantum Dots" _invited_ *Advances in Atomic, Molecular, and Optical Physics,* Vol 64, Susanne Yelin, editor, Elsevier, Oxford (2015).

    15. A. P. Burgers, J. R. Schaibley and D. G. Steel, "Entanglement and Quantum Optics with Quantum Dots," _invited_ *From Atomic to Mesoscopic,* ITAMP, Harvard, World Scientific Reviews (2015).

Invited conference papers

1. D.G. Steel, "Coherent Optical Control of Electron and Nuclear Spins in a Quantum Dot," American Physical Society, March Meeting, Pittsburg 2009

2. D.G. Steel, "Fast Coherent Optical Manipulation of Quantum Dots and the Nuclear Servo" Materials Research Society, Boston, Fall 2009.

3. D.G. Steel, "Coherent Optical Manipulation of Electron and Nuclear Spin in Artificial

Atomic and Molecular Systems in Solids," Invited Talk, Isakson Prize Lecture, APS March Meeting, 2010.

4. D.G. Steel, "Optically Driven Spins in Semiconductor Quantum Dots: Toward III-V Based Quantum Computing," DPG Physics School 2010 on "Nano-Spintronics", Bad Honeff, Germany.

5. D.G. Steel, "Coherent optical control of the nuclear and electron spin in quantum dots: Fast rotations and a geometrical phase gate," 6th International Conference on the Physics of Quantum Dots (QD2010), Nottingham, UK.

6. Bo Sun, Colin Ming Earn Chow, and Duncan G. Steel, Allan S. Bracker and Daniel Gammon, L. J. Sham, "Persistent Optical Nuclear Spin Narrowing" Frontiers in Optical Physics in Semiconductors, Lake Junaluska, North Carolina (2011).

7. D.G. Steel. "Optical Control of the Electronic and Nuclear States in a Single Quantum Dot," OSA 96th Annual Meeting, FiO/LSXXVIII , Rochester New, New York (2012).

8. D.G. Steel, "Coherent Optical Control of Electronic and Nuclear States in a Quantum Dot," The University of Michigan Quantum Summer School, Ann Arbor (2012).

9. D.G. Steel, "Coherent Control of Electronic and Nuclear States in a Quantum Dot: A New Dimension for Modern Photonics," Cavendish Physical Society, Cambridge, UK (2012).

10. John R. Schaibley, Alex P. Burgers, Greg A. McCracken, Luming Duan, Paul R. Berman, Duncan G. Steel, Allan S. Bracker, Daniel Gammon, Lu J. Sham, "Spin-Photon Entanglement and Optical Control of Quantum Dots: Steps toward Quantum Information Processing", Frontier in Optical Physics of Semiconductors, Kodiak Island, Alaska (2013).

11. D.G. Steel, "Coherent Control of Electronic and Nuclear States in a Quantum Dot: A New Dimension for Modern Photonics, " Harvard Institute of Theoretical Atomic and Molecular Physics (ITAMP, Cambridge) 2014.

12. D.G. Steel, "Coherent Control of Electronic and Nuclear States in a Quantum Dot: A New Dimension for Modern Photonics" University of Halifax Colloquium (2014).

13. D.G. Steel "Optical Control of Electron and Nuclear States"Frontiers in Optics 2014/Laser Science XXX (FiO/LS) Tucson, AZ (2014).

14. A. Burgers, D.G. Steel, "Coherent Optical Control of Quantum Dots: Spin Qubits and Flying Qubits", APS March Meeting, San Antonio, TX, 2015.

15. D.G. Steel, "Coherent optical control of the nuclear and electronic degrees of freedom in

single and coupled semiconductor quantum dots", Frontiers in Optical Physics in Semiconductors, Breckinridge, Colorado (2015)

Conference presentations

1. Bo Sun, Xiaodong Xu, Paul R. Berman, and D. G. Steel A. S. Bracker and D. Gammon, L. J. Sham, "Coherent Population Trapping of an Electron Spin in a Single Negatively Charged Quantum Dot," IQEC (Baltimore, 2009).

2. Bo Sun, Xiaodong Xu, and D. G. Steel Wang Yao, A. S. Bracker and D. Gammon, L. J. Sham, "Optically Controlled Locking of the Nuclear Field via Coherent Dark State Spectroscopy," IQEC (Baltimore, 2009).

3. Erik D. Kim, Katherine Smirl, Xiaodong Xu, Bo Sun, Duncan Steel, Allan Bracker, Dan Gammon, and Lu Sham, "Coherent Ultrafast Optical Control of an Electron Spin Initialized to a Pure State in a Charged Self-Assembled Quantum Dot, " IQEC (Baltimore, 2009).

4. Erik D. Kim Erik D. Kim, Katherine Truex, Xiaodong Xu, Bo Sun and D. G. Steel, A. S. Bracker D. Gammon, L. J. Sham "*A Spin Phase Gate Based on Optically Generated Geometric Phases in a Self-Assembled Quantum Dot,"* QELS (San Jose, 2010).

13. John Schaibley, Alex Burgers, Gregory McCracken, Luming Duan, Paul Berman, Duncan Steel, Allan Bracker, Daniel Gammon, and Lu Sham, "*Entanglement between a Quantum Dot Spin and a Photon*" CLEO/QELS, San Jose, CA (2013).

14. John Schaibley, Alex Burgers, Gregory McCracken, Luming Duan, Paul Berman, Duncan Steel, Allan Bracker, Daniel Gammon, Lu Sham "*Quantum Dot Spin-Photon Entanglement*" Rochester Conferences on Coherence and Quantum Optics (CQO) and Quantum Information and Measurement (QIM), Rochester (2013).

15. Colin M. Chow, Aaron M. Ross, Daniel Gammon, Allan S. Bracker, L. J. Sham, Duncan G. Steel, "Optical Spin State Preparation of Two Electrons Confined in an InAs Quantum Dot Molecule," CLEO/QELS San Jose (2015).

16. Aaron M. Ross, Colin M. Chow, Daniel Gammon, Allan S. Bracker, L. J. Sham, Duncan G. Steel, "Nuclear Spin Narrowing in an InAs Quantum Dot Molecule: Extension of Two-Electron Spin Decoherence Time," CLEO/QELS, San Jose (2015.

17. Bo Sun, Colin Chou, Duncan Steel, Allan Bracker, Dan Gammon, LJ Sham, "Increasing Quantum Dot Electron Spin Coherence with Persistent Spin Narrowing" APS March Meeting, (2011).

18. Leon Webster, Katherine Truex, L.-M. Duan, L.J. Sham, A.S. Bracker, D.Gammon, and D.G. Steel, “Precursor to spin-photon entanglement in a single InAs/GaAs quantum dot” Frontiers in Optical Physics in Semiconductors, Lake Junaluska, North Carolina (2011).

19. John Schaibley, Duncan G. Steel, Allan S. Bracker and Daniel Gammon, L. J. Sham, “” Frontiers in Optical Physics in Semiconductors, Lake Junaluska, North Carolina (2011).

20. Vasudev Lal, Duncan Steel, Roseanne Sension, “Indication of Long Lived States in Decay Associated Spectra of Single-Walled Carbon Nanotubes,” APS March Meeting (Boston), 2012.

21. John Schaibley, Alex Burgers, Greg McCracken, Luming Duan, Paul Berman, Duncan Steel, Allan Bracker, Daniel Gammon and Lu Sham, "Observation of quantum entanglement between a photon and a single electron spin conned to an InAs quantum dot,"American Physical Society March Meeting, Baltimore, MD, 2013.

22. J. R. Schaibley, A. P. Burgers, G. A. McCracken, L.-M. Duan, P. R. Berman, D. G. Steel, A.S. Bracker, D. Gammon and L. J. Sham, "Quantum Dot Spin-Photon Entanglement," Rochester Conferences on Coherence and Quantum Optic, Rochester, NY, 2013

23. A. P. Burgers, J. R. Schaibley, G. A. McCracken, L.-M. Duan, P. R. Berman, and D. G. Steel A.S. Bracker and D. Gammon L. J. Sham, Demonstration of Entanglement between a photon and a Quantum Dot, APS Division of Laser Science Annual Meeting, Laser Science (Orlando), 2013.

24. Colin M. Chow, Zhexuan Gong, Luming Duan, Duncan G. Steel “Proposal for a Universal Two-Qubit Quantum Gate in Self-Assembled InAs/GaAs Quantum Dot Molecules with Intensity-Modulated CW Laser”, APS Division of Laser Science Annual Meeting, Laser Science (Orlando), 2013.

25. Colin M. Chow, Zhexuan Gong, Luming Duan, and Duncan G. Steel, “Proposal for an All-Optical Universal Two-Qubit Quantum Gate in InAs Quantum Dot Molecules” Frontier in Optical Physics of Semiconductor (FOPS), Kodiak Island, Alaska (2013).

26. Colin M. Chow, Aaron M. Ross, Lu J. Sham, Allan S. Bracker, Daniel Gammon, Duncan G. Steel, “Nuclear Spin Locking and Extended Two-Electron Spin Decoherence Time in an InAs Quantum Dot Molecule,” APS March Meeting, San Antonio (2015).

27. Aaron M. Ross, Colin M. Chow, L. J. Sham, Allan S. Bracker, Daniel Gammon, Duncan G. Steel, “Ground state initialization in a doubly-charged, vertically-stacked InAs quantum dot molecule,’ APS March Meeting, San Antonio (2015).

EDUCATIONAL ACTIVITY

A number of students (10) participated in the program as evidenced in the above publications. Nine of the students have since graduated with a Ph.D and gone on to postdocs or permanent positions including one as a tenure track faculty member at Univ. Wash. – Seattle and another at Univ. S. Carolina – Columbia. Several new students have joined the group and are involved in the program.

COLLABORATIONS

The work in the program is the result of an intense collaboration with Dr. D. Gammon at The Naval Research Laboratory to develop quantum dot structures and spintronic based devices. A collaboration has also been started with Sven Höfling (Univ. Wurzburg) on a new kind of sample designed to exploit cavity coupling to the dot to enhance brightness for production of flying qubits. A collaboration was also begun with Prof. Zetian Mi (Univ. McGill) to study GaN dots which might work for information at room temperature. In addition, the many body theory component of the analysis of our findings is supported through our collaboration with Professor L.J. Sham (UCSD), supported by ARO, AFOSR and NSF. Work on the quantum physics of light-matter interactions is based in part on a long time collaboration with Prof. PR Berman (UMi). All work on the demonstration entanglement and quantum gates was done in close collaboration with Luming Duan (UMi). A collaboration was also begun with Prof. Paul Kwiat (Univ. Ill.) to build a high brightness spontaneous photon down conversion source for teleportation work. I have also had technical discussions with Dr. Paul Alsing, AFRL.

OBJECTIVES

The primary goal of this proposal is to demonstrate full coherent control of individual electronic spins in a single quantum dot and to show that adjacent dots can be coherently manipulated to form arbitrary states including entangled states between at least two separate qubits.

There research program was based on exploiting the main results of the previous research period, namely that (1) we could freeze the nuclear spin fluctuations[1], which leads to a dramatic reduction in the decoherence rate of the electron spin qubit, increasing the spin qubit coherence lifetime to at least 1 microsecond, and (2) we could arbitrarily manipulate a single electron spin qubit [2]. The measurements capitalized on our unique capability for ultrahigh resolution coherent nonlinear optical spectroscopy developed over the years on this program as well as coherent transient spectroscopy based on conventional ultrafast technology. We are also developing new capability based on fiber-optic modulators to integrate diode laser sources and fast EO modulators to provide fast pulses with special pulse shaping to test new proposals for adiabatic type state manipulation at high modulation rates. Specifically, the following experimental objectives formed the scientific directions of the research:

1. *To demonstrate arbitrary spin state preparation and rotation of the two state spin system of a single electron doped in a single self-assembled quantum dot using both AM and FM switching and two-photon stimulated Raman excitation using 1-photon resonance enhancement through the trion state.*
2. *To use the ultrahigh resolution spectroscopy technique proposed by us[3] to measure the spin coherence time and determine the time as a function of the degree of spin state mixing (determined by the angle of magnetic field in the y-z plane where z is the growth direction and y is perpendicular to the growth direction) in order to*

provide the data base needed to design structures which combine all the features of initialization, switching, and readout.

3. *Demonstrate high speed repetitive coherent switching and extended coherence times (based on concatenated pulses to reverse decoherence) to enable testing of concepts for (quantum) computing and other applications and to extend the coherence time in these systems to the ultimate time scale on the order T1 (~msec)[4].*
4. *To demonstrate coherent optical control of state mixing using the AC Stark effect for fast tuning.*
5. *To demonstrate arbitrary spin-state preparation of two electrons localized in separate but adjacent quantum dots using high-speed optically based spin cooling techniques.*
6. *To demonstrate dynamically controlled excited state interactions needed to produce arbitrary coherent superposition states of the eigenstates of the two spins in both dots. Ultimately, these experiments would lead to production of arbitrary entangled states and various gate operations*

As discussed in the previous reports and in this final report, considerable progress has been made toward the above long term objectives. Current work is continuing in line with the above objectives.

SUMMARY OF FINDINGS

Nearly all of the research findings presented in this report have been reported in the annual reports. However, for completeness, we list the major developments, and we review a few of the most recent important results.

Introduction

The transfer of optical coherence to electronic coherence has featured prominently in current research as many new applications seeking to exploit the potential of this relatively new form of control. Ultimately, it may be possible to imagine nanophotonic/electronic materials which are controlled optically rather than an increasing density of individual metallic wires and connections. Control in atomic and molecular systems is considerably advanced. However, control in semiconductor systems remains under active development and rapid evolution.

In this program, we built on our previous work demonstrating that quantum dot structures interact with coherent radiation similarly to atomic systems, unlike higher dimensional semiconductor systems that are characterized by complex many body interactions. We are using engineered structures that have had their electronic structure modified to create the ideal 3-level Λ system needed for applications requiring long coherence times (the two ground states are different carrier spin states) such as in quantum computing, and storage devices based on slow light and lasing without inversion.

The goal of the program is to demonstrate that the essential physical features can be seen in these systems and coherently controlled. Ultimately, the coherence time in these systems is limited by spin dephasing which can be very long, in principle. In III-V materials, this time is limited by fluctuations in the hyperfine coupling to 104 or so nuclei in a given dot. Control of the electronic and nuclear degrees of freedom in III-V type material, as we describe in this report, open the door to developments that would naturally lead to easy integration with other optoelectronic devices.

Our approach to the study and manipulation of electron spin for application to spin based devices is based on the use of coherent nonlinear laser spectroscopy, coherent transient excitation and optical control, and the use of advanced semiconductor materials. Specifically, the electron spin, which would also correspond to the qubit for applications in quantum information science, is confined to a semiconductor quantum dot. Ultrafast coherent control of the electronics states which are separated in energy in the RF and microwave region of the spectrum is achieved by coherent optical excitation using the trion state (a negative exciton) as an intermediate state, thus allowing optical frequencies (eV) to be used to manipulate the spin states, typically separated by 10's of μeV. Materials are grown by MBE and further processed by lithography techniques by our collaborators.

For quantum computing, a scalable architecture has been published by our collaborators (Lu J. Sham, UC-SD) based on individual qubits (electron spins) confined in adjacent quantum dots. Entanglement between spin in adjacent dots is accomplished by a modified optical RKKY (ORKKY) interaction resulting in a Heisenberg Hamiltonian coupling between the two spins.

Figure 1 shows the basic energy level diagram for a single InAs self-assembled quantum dots (QD) charged with a single electron and the corresponding optical selection rules for dots in an x-oriented magnetic field (Voigt profiles) resulting from addition of one electron. Two 3-level Λ-systems are produced. Relaxation between the two states is determined by spin relaxation and is known to be long, relative to the exciton relaxation time. The long relaxation time is expected to lead to long coherence times.

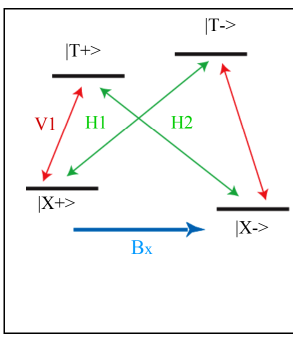

Figure 1. Energy level diagram for the negatively charged heavy hole exciton and polarization selection rules for a magnetic field in the Voigt direction in InAs.

The usually forbidden optical transition between the trion state and the other spin state is allowed in the presence of a magnetic field in the x-direction (Voigt profile). Coherent optical control of the spin states is then enabled through a stimulated Raman two-photon (SR2P) pathway, shown by the red and green arrows. This structure has been the foundation of all of our single qubit measurements in this program.

Figure 2 shows the energy level diagram for the (bipartite) two qubit system based on coupled quantum dots. This structure is also referred to as a quantum dot molecule (QDM). The energy level structure and selection rules were determined by numerical simulations of the whole solution to Schrödinger's equation in the effective mass approximation. The details of this and the role of Coulomb exchange coupling and discrete charging are discussed in an earlier report and in a manuscript in preparation [5].

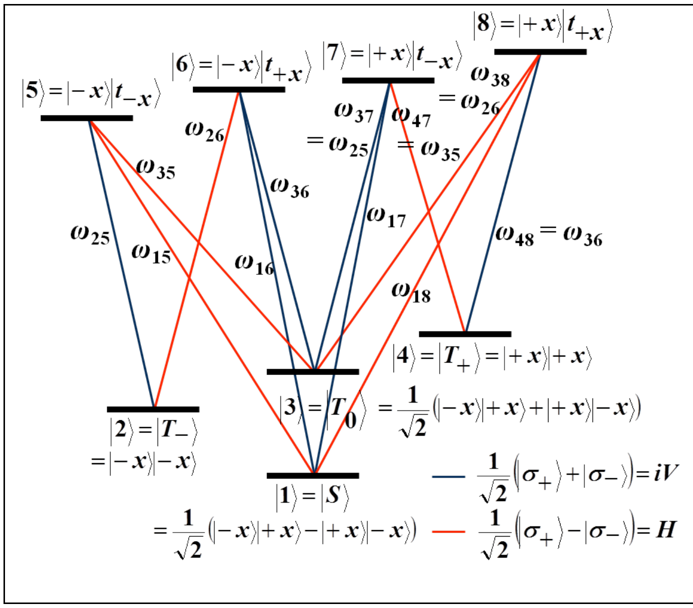

Figure 2. The eight-level system of the doubly charged QDM and selection rules for optical transitions in 1.5 Tesla transverse magnetic field (Voigt geometry). The optical ground states are in singlet (J = 0) and triplet (J = 1) manifolds while the optical excited states in this study consist of an electron in the lower QD, represented by $|\pm x\rangle$, and a trion in the upper QD, represented by $|t_{\pm x}\rangle$. Here, spin projections are shown along +x-direction (the direction of the magnetic field) and + (−) denotes spin up (down). Dark blue lines represent vertically (V) polarized optical fields while red lines represent horizontal (H) polarization. The theory we developed for this was presented in an earlier report [5].

Summary of the most important achievements over the funding period:

Demonstration of spin rotation and a geometrical phase gate in a quantum dot.

Measurement of the nuclear spin fluctuation freezing dynamics resulting in 2 orders of magnitude increase in the electron spin coherence time, showing onset ~10msec and lifetimes>>1 sec.

Full design and numerical simulation of coherent optical control leading to deterministic spin-photon entanglement.

Experimental demonstration of coherent control to prepare an InAs quantum dot for spin-photon entanglement

First measurement of Rabi oscillations as a function of real time in a quantum dot.

Demonstration of quantum entanglement between the spin polarization states of single quantum dot electron and the polarization states of a spontaneously emitted photon

Demonstration of nonlocal nuclear spin polarization and nuclear spin fluctuation freezing.

Demonstration of the initialization of 3 of the 4 ground states in a quantum dot with numerical simulations showing full initialization of the 4th state with additional optical control.

The balance of this report will feature our most recent and important results. Previous work is summarized above and detailed in previous annual reports.

Ground state initialization in a doubly-charged, vertically-stacked InAs quantum dot molecule

One of the primary objectives of this research is to demonstrate an all optically controlled universal gate. This requires the ability to initialize each of the states. We demonstrated this earlier in the single quantum dot, but the energy level structure shown in Fig. 2 shows the problem is more complicated with eight levels. At this point in our work, we have developed optical pumping schemes that have allowed us to initialize three of the four ground states, S, T_+, and T_-. An example of the pumping scheme to initialize the singlet state is shown in Fig. 3 where the solid lines represent the optical pumping fields and the dashed lines represent the optical field (probe) used to make measurements of the fidelity. Figure 4 shows the fidelity table for the 3 states that we have achieved. Higher fidelity is likely at higher magnetic fields but then precession frequency will begin to exceed our current detector timing resolution for controlled operations.

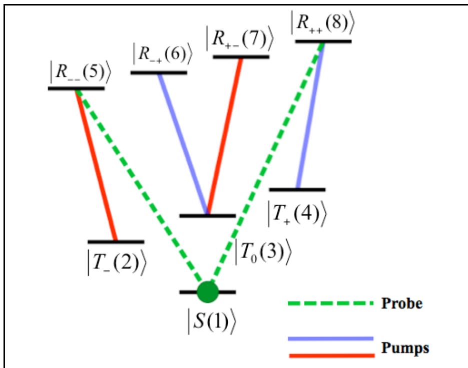

Figure 3. An example of initialization by optical pumping. Here, the singlet state is initialized. Pump frequencies are color coded (solid) and exploit the transition energy degeneracies. The probe is dashed and, by polarization selection rules, couples to two nondegenerate transitions to make the measurement.

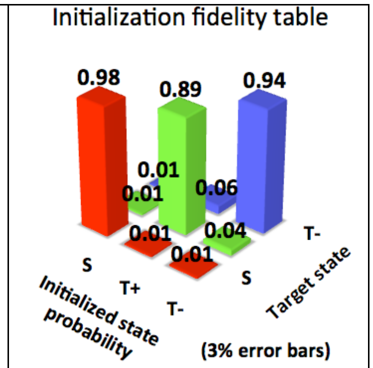

Figure 4. Initialization fidelity table for 3 of the 4 states comprising the ground state manifold of the coupled quantum dot molecules, where each quantum dot is charged with a single electron.

Absent from the data in Fig. 4 is the T_0 state. An examination of the energy levels in Fig. 2 shows the additional complexity of this problem because of the accidental degeneracy of four of the optical transitions. There are various optical methods that can resolve this, but our simulations show the most straightforward approach is by adjusting the intensities of the optical pumping fields which then assures that we can asymptotically approach unity, as shown in Fig. 5. The experimental demonstration of this is underway, but is more complicated because the readout of the initialized state in this setup has to be by spectrally filtered resonant Rayleigh scattering to avoid noise from the pump fields.

Nuclear local and nonlocal spin locking and extended two-electron spin coherence in an InAs quantum dot molecule

In 2009, we reported in Nature the first observation of optically modifying the Overhauser field (also called dynamic nuclear spin polarization, DNSP) and the corresponding of locking of nuclear spins (i.e., quieting or freezing of the spin fluctuations) that resulted in at least two orders of magnitude increase in the electron spin coherence time. The data featured hysteresis as function of laser scanning direction and unusual line shapes, reflecting the change in the local Overhauser field as well as a dramatic increase in the dip demonstrating coherent population trapping, a key signature of the creation of a dark state in electromagnetic transparency measurements. The increase in the depth of the dip was a direct measure of the increase in the electron spin coherence time.

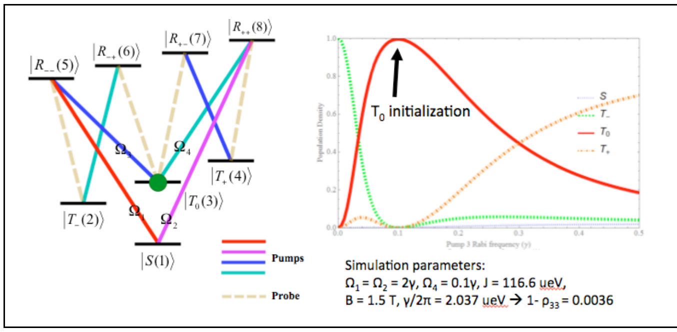

Figure 5. Left: Level diagram and arrangement of pumping fields and probe field. Right: Simulation showing initialization of the T_0 state using 4 optical pump fields. See text for discussion. The dark arrow shows the intensity where T_0 is maximized and the other state populations are minimized.

Confirmation of the DNSP effect in the molecule was helpful in terms of supporting our earlier claim, however, with 8 states involved in the dot and the degeneracy of the 4 transitions, we quickly understood that locking the system into a well defined nuclear configuration as we did in the 2009 paper was going to be considerably more complicated.

After considerable effort, we found that we could simultaneously suppress the nuclear spin fluctuations in both upper and lower quantum dots (QDs) while optically addressing only the upper QD transitions. The demonstration required three separate lasers to stabilize the nuclear spin polarization, a fourth laser (a probe field) for enabling CW dark-state spectroscopy to measure the change in the electron spin decoherence rate. Nuclear spin narrowing is again revealed through the emergence of prominent dark-state dips where again the degree of the transparency, i. e., the depth of the dip, provides a direct measurement of the two-electron spin decoherence time between arbitrary pairs of states in the singlet-triplet ground state manifold of the QDM. An example of the data is shown in Fig. 6a (showing the arrangement of locking pumps) and Fig. 6c showing the appearance of the dark state dips.

One of the important consequences of this result is demonstrating that the spin locking mechanism has additional complexity which contribute to increasing it's importance in device designs. Specifically, while the optical fields excite only the upper QD trion, nuclear spin locking in the other QD appears to be channeled by the delocalized electron wavefunctions.

In addition, we have found that by careful analysis of the line shape associated with the spectral response leading to CPT and electromagnetic induced transparency (EIT), we have mapped out the Overhauser magnetic field distribution that leads to the modified lineshape. An example of the result is shown in Fig. 6b, with and without one of the pump fields that also dramatically demonstrates the narrowing of the field distribution with the additional pump. This data will be important in future ideas for exploiting this behavior for potential long term information storage as well as development of the full theoretical model for this process.

The optically induced locking of the Overhauser field and the quieting of nuclear spin fluctuations extends the applications of InAs QDMs to include the entire singlet-triplet manifold, and further establishes the potential of InAs QDs in addressing the challenge of scaling up quantum computation and communication. The locking demonstration is essential since there is no detectable electron spin coherence in the absence of spin locking.

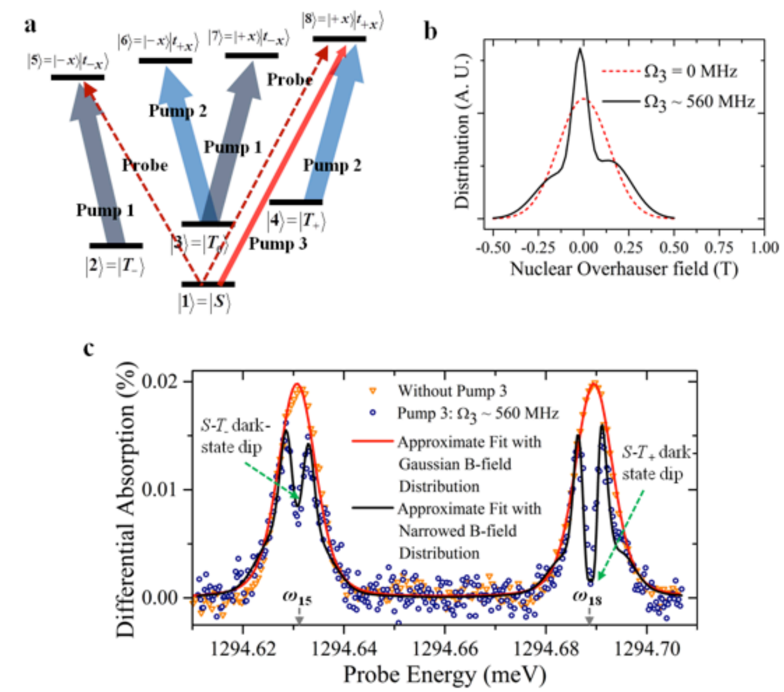

Figure 6. Singlet-triplet coherence and nuclear field distribution narrowing. a. Pump configuration for preparation of a coherent S-T_+ superposition. b, Nuclear field distributions used in the numerical model of the master equations for fitting the spectra in c. When a strong pump is resonant with the S to T_+ transition, the Overhauser field distribution shows a central narrowing (solid black line) which results in a clear dark state dip in the absorption spectrum shown in 6c.   c. Absorption spectra showing the emergence of dark-state dips from S-T_- and S-T_+ coherence at transitions ω_{15} and ω_{18}, respectively, following the application of Pump 3, with Ω_3 = 560 MHz, together with numerical fits using nuclear field distributions shown in b.

Summary and future directions

This program has resulted in new understanding of importance to coherent optical control of epitaxially grown quantum dots. The studies continue to focus on demonstrating mulitqubit entanglement using both photon heralded spin entanglement for spins separated by a distance and Coulomb exchange coupling in vertically stacked quantum dots. We have expanded considerably, also, in our understanding of the Overhauser field and to control that field even in the presence of more than a single electron. Our future work is to complete these studies and continue the analysis of dots for application to classical information processing as well as extending our studies of the optically induced nuclear state.

[1] X. Xu, W. Yao, B. Sun, L.J. Sham, D.G. Steel, Control of Nuclear Spin by Coherent Trapping of Electron Spin, Nature, 459 (2009) 1105-1109.
[2] E.D. Kim, K. Truex, X. Xu, B. Sun, D.G. Steel, A.S. Bracker, D. Gammon, L.J. Sham, Fast Spin Rotations by Optically Controlled Geometric Phases in a Charge-Tunable InAs Quantum Dot, Phys. Rev. Lett., 104 (2010) 167401.

[3] R.B. Liu, S.E. Economou, L.J. Sham, D.G. Steel, Theory of nonlinear optical spectroscopy of electron spin coherence in quantum dots Phys. Rev. B, 75 (2007) 085322.
[4] R. Hanson, L.H. Willems van Beveren, I.T. Vink, J.M. Elzerman, W.J.M. Naber, F.H.L. Koppens, L.P. Kouwenhoven, L.M.K. Vandersypen, Single-Shot Readout of Electron Spin States in a Quantum Dot Using Spin-Dependent Tunnel Rates, Physical Review Letters 94 (2005) 196802.
[5] C.M.E. Chow, L.J. Sham, D.G. Steel, A single-Band Effective-Mass Model of Energy Level Structures in Self-Assembled InAs Quantum Dot Molecules, in preparation, (2016).